JOINING OF DISSIMILAR MATERIALS USING ND: YAG LASER WELDING

A Thesis submitted to the

National Institute of Technology, Rourkela

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of

Bachelor of Technology (Mechanical Engineering)

By

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CERTIFICATE

This is to certify that the project entitled, "JOINING OF DISSIMILAR MATERIALS USING Nd: YAG LASER WELDING**"** submitted by Mr. Amit Kumar Barik in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance, and the information contained in this report is true to the best of my knowledge.

Date: 13th May, 2010

Place: Rourkela

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Date: 13th May, 2010

Place: Rourkela

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Mechanical engineering

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ABSTRACT

The combination of mild steel and stainless steel as a welded joint has very important applications in industry. In this project, laser welding of mild steel to stainless steel was studied at different values of beam energy and welding speed, keeping beam diameter constant. A 9 kW ALPHALASER AL200 Nd:YAG laser was used to weld 1.5 mm thick mild steel and stainless steel plates. The photographs of the welded seams were observed and tensile testing of specimens was done to evaluate the mechanical properties of the welded joint. The peak load at which each specimen broke was found out. Results indicated that with an increase in values of both welding speed as well as beam energy, the peak load first increased gradually, attained a maximum, and then decreased. Equations were found out to depict the relation between (i) peak load and beam energy and (ii) peak load and welding speed.

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CHAPTER

1

INTRODUCTION

1.1 BACKGROUND

Even in this modern era of technology, one thing that has remained unchanged is the use of metals. Without metals, it is impossible to imagine even the most basic of things. Metals like iron, copper, aluminium, steel, etc and their various alloys continue to be used in our day to day life. In many instances, it is often required to use a combination of different metals, rather than a single metal, to achieve certain objectives. In such cases, metal joining methods are employed, to join one metal to the other, without any loss of properties of the individual materials.

Talking of metal joining processes, there are a lot of options namely:

- ❖ Brazing
- ❖ Welding
- ❖ Soldering
- ❖ Mechanical bonding
- ❖ Adhesive bonding

Depending upon the particular properties required, each of these processes can be employed with their inherent merits and demerits, however, for strong joints, welding is the best available option.

1.2 WELDING

Welding is a metal fabrication process which is used to join metals by the phenomenon of coalescence. The work-pieces are melted using heat derived from various energy sources such as a gas flame, an electric arc, friction, ultrasound, electron beam, laser energy, etc., to produce a pool of molten metal (weld pool), which on cooling solidifies to form very strong joints. Use of filler material and application of pressure is also done in order to achieve better and stronger joints.

The various types of welding methods normally employed are:

- ❖ Arc welding
- Shielded metal arc welding (SMAW)
- Gas metal arc welding (GMAW)
- Flux-cored arc welding (FCAW)

- Gas tungsten arc welding (GTAW), or tungsten inert gas (TIG) welding
- Submerged arc welding (SAW)

❖ Gas welding

- Oxy-acetylene welding
- Air acetylene welding

❖ Resistance welding

- Spot welding
- Seam welding

❖ Energy beam welding

- Laser beam welding
- Electron beam welding
- X-ray welding

❖ Solid-state welding

- forge welding
- ultrasonic welding,
- explosion welding

Of particular importance in both joining of similar and dissimilar metal combinations is the technique of laser welding, which is undergoing lots of improvements nowadays.

1.3 LASER WELDING

Laser beam welding (LBW) is a unique welding technique used to join metals through the heating effect of a concentrated beam of coherent monochromatic light known as LASER. Light amplification by stimulated emission of radiation (LASER) is a mechanism which emits electromagnetic radiation, through the process of simulated emission. LASER light is generally a spatially coherent, narrow-wavelength electromagnetic spectrum monochromatic light.

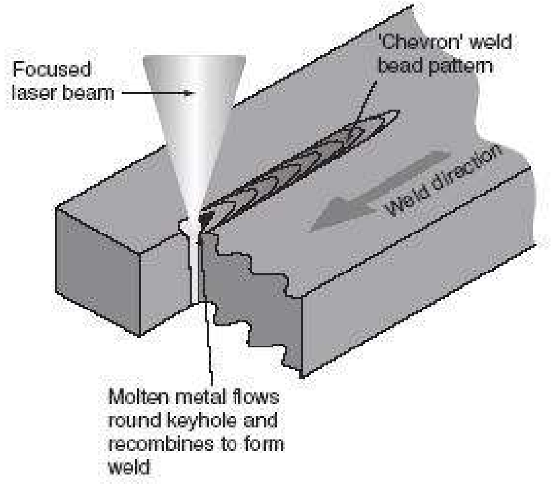

Fig 1.1: Principle of Laser Welding

Laser beam welding has high power density (of the order of 1 Megawatt/cm^2 (MW)), having high heating and cooling rates which result in small heat affected zones (HAZ). Industrial lasers are used for welding, cutting, drilling and surface treatment of a wide range of engineering materials. An inert gas, such as helium or argon, is used to protect the weld bead from contamination, and to reduce the formation of absorbing plasma. Depending upon the type of weld required a continuous or pulsed laser beam may be used.

LBW is a very versatile process, which is capable of welding a variety of materials like stainless steels, carbon steels, aluminum, copper, tool steels, etc. The weld quality is high, although some cracking may occur in the weld region. The speed of welding is proportional to the amount of power supplied but also depends on the type and thickness of the work-pieces. Laser welding is of particular interest in the automotive industry, laser welding has been applied for joining sheet body panels, transmission components and chassis members during production [13].Quite recently, LBW has also been utilized to manufacture hybrid micro-systems consisting of different materials[14].

1.4 LASER WELDING EQUIPMENT

Basically two types of laser equipment are in use, solid-state lasers and gas lasers. Solid-state lasers employ solid media, like synthetic ruby, yttrium aluminum garnet crystals doped with neodymium (Nd:YAG), chromium in aluminum oxide, etc. Gas lasers use carbon dioxide, nitrogen, etc as medium. The medium, when excited, emits photons and forms a laser beam.

1.4.1 Solid state laser

The most popular solid state design is a rod shaped single crystal approximately 20 mm in diameter and 200 mm long with flat grounded ends. A flash tube, containing xenon or krypton surrounds this tube. When flashed, a pulse of light lasting about two milliseconds is emitted by the laser.

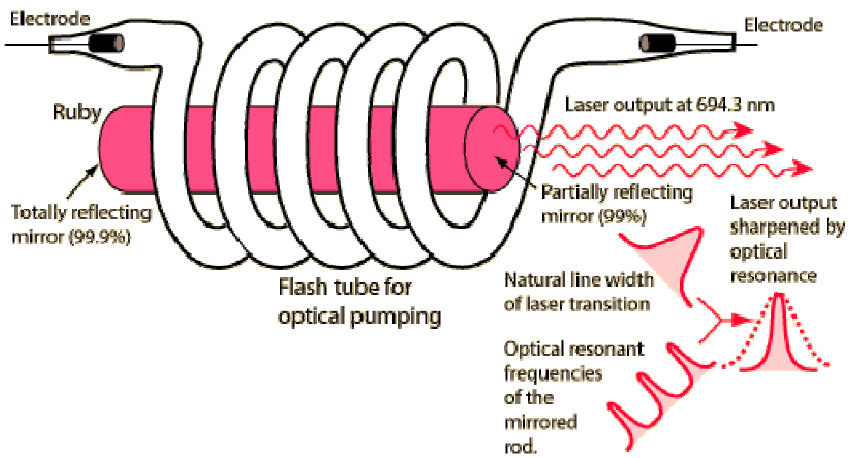

Fig1.2: Schematic of a solid-state Ruby laser

Nd:YAG lasers can operate in both pulsed and continuous mode providing power outputs between 0.04–6000 W. Solid-state lasers operate at very low wavelengths, and hence cannot be operated with the naked eye. Operators must wear special eyewear or use special screens to prevent damage to the retina.

1.4.2 Gas laser

In gas lasers, the lasing medium (gas mixture) is excited by using high voltage, low current power sources. Power outputs for gas lasers can be much higher than solid-state lasers, and these lasers can operate both in continuous as well as pulsed mode.

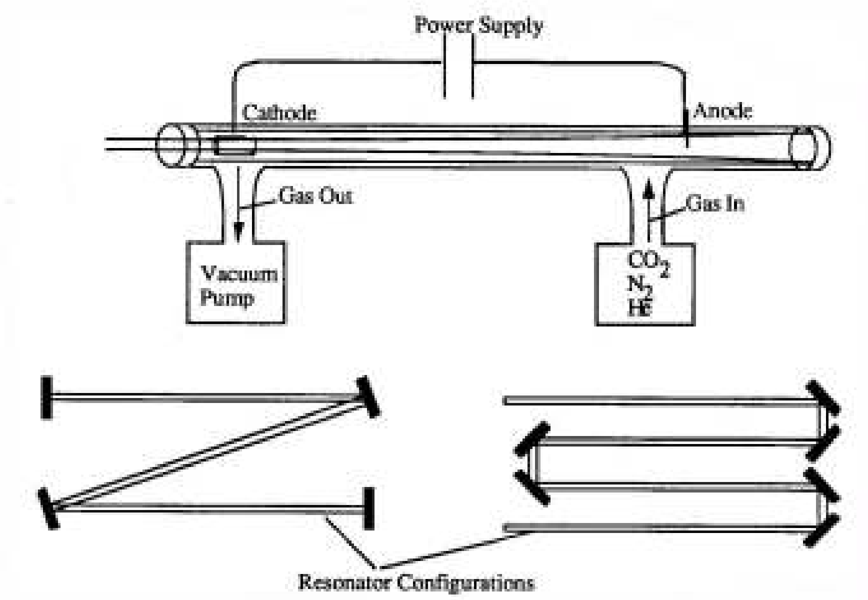

Fig1.3: Axial Flow CO2 laser (After Chryssolouris, 1991)

1.4.3 Fibre laser

In fiber lasers, the gain medium is the optical fiber itself. They are capable of power up to 50 kW and are increasingly being used for robotic industrial welding.

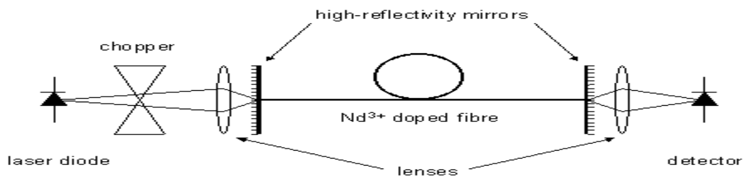

Fig1.4: A diode-pumped Fibre laser

1.4.4 Nd:YAG laser

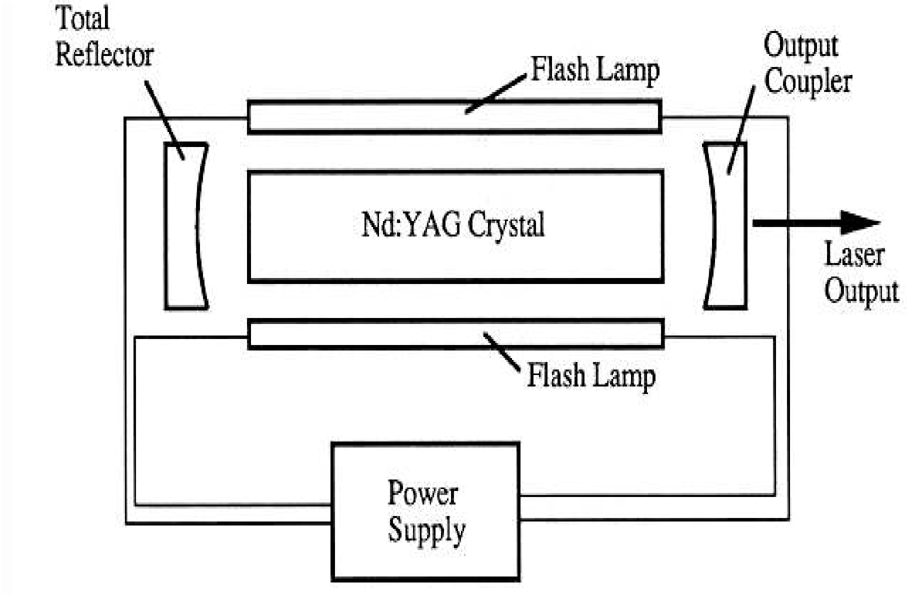

Fig1.5: Schematic of Nd:YAG laser (After Chryssolouris, 1991)

The Nd: YAG laser is an optically pumped solid state laser system that is capable of providing high power laser beam. The lasing medium is a colorless and isotropic crystal Yttrium aluminium garnet (YAG: $Y_2Al_5O_{12}$) having a four operational levels of energy.

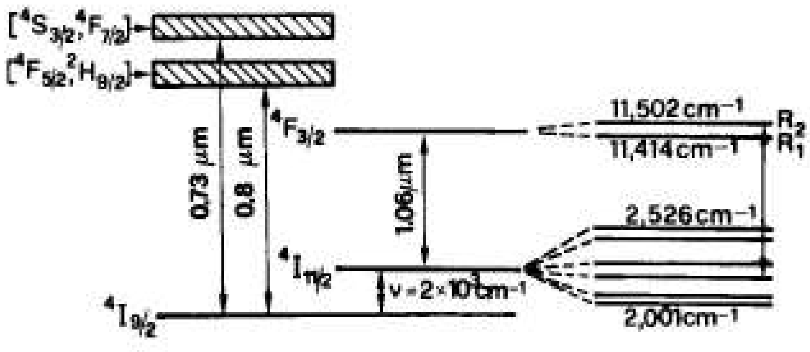

Fig1.6: Energy levels of Nd: YAG laser

The yttrium aluminium garnet is doped with some amount of neodymium. When sufficiently intense light is allowed to fall on this crystal, population inversion occurs and atoms in the crystal structure absorb this incident light to perform transitions from the ground state to the absorption bands. This is often done with the help of a flash tube.

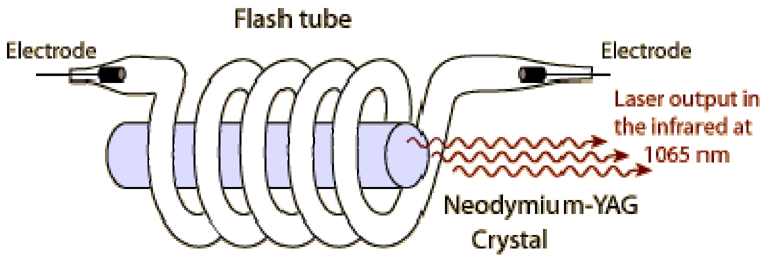

Fig 1.7: Nd: YAG laser system showing the flash tube

The transition from the absorption bands to the upper energy laser levels is very smooth. The decays from these higher levels back to the ground state are longer in duration than the transitions to the higher levels. Due to this long lifetime, the atoms de-excite back to the ground states almost spontaneously, thus producing a laser beam.

Commercial Nd: YAG lasers for welding applications are available from many suppliers. These lasers may be operated in three modes:

1. Continuous output
2. Pulsed pumping
3. Q-switched mode

The following table shows the different output characteristics of an Nd: YAG laser at various conditions of excitation.

TABLE 1: Output characteristics of Nd: YAG lasers under different excitation conditions [16]

Mode	Average Power (kW)	Peak power (kW)	Pulse Duration	Pulse Repetition Rate	Energy/Pulse (J)
Continuous	0.3-4	-	-	-	-
Pulsed	To 4	To 50	0.2-20 msec	1-500 Hz	To 100
Q-switched	To 4	To 100	<1 μsec	To 100 kHz	10^{-3}

One of the prime advantages of the Nd: YAG laser is the ability to deliver laser radiation through optical fibers, even over several hundred meters with minimal loss.

1.5 MODES OF LASER WELDING

When using laser for welding purposes, energy is transferred from the laser to the work-piece through two different ways or modes. The laser welding mode can be either the conduction mode or the keyhole mode depending upon the power density. The two modes of laser welding are:

1.5.1 Conduction limited mode

It is a low energy density process, which basically heats the surface of the material being welded. The beam energy is deposited on the material surface, conducted into the material, forming a hemispherical bead. The size of the weld on the surface is generally larger, and the depth of penetration of the weld is generally shallower. Power densities lie below 10^6 W cm^{-2}.

1.5.2 Keyhole mode

In this mode of laser operation, power densities lie between 10^6 W cm $^{-2}$ and 5 x 10^7 W cm $^{-2}$. A narrow, deeply penetrating vapour cavity, or keyhole, is formed due to local vaporization. The keyhole is surrounded by a thin layer of molten material. This layer is maintained by equilibrium between vapour pressure, surface tension and hydrostatic pressure. Material at the leading edge is melts and flows around the keyhole, solidifying to form a deep, narrow weld bead. Heat affected zones (HAZ) are very narrow.

1.6 PROCESSING PARAMETERS

Laser power, q (W), welding velocity, v (ms^{-1}), r_B (m) and focused beam diameter are the three main parameters which affect a laser welding process. Other than these three, other parameters derived from these three basic parameters also play a major role in determining the weld pool properties. They are Power density, q/r_B^2 (W m^{-2}), energy per unit weld length, q/v (J m^{-1}), and energy per unit weld volume, q/ (vd) (J m^{-2}); where d is the plate thickness.

Study of various analytical models of deep penetration welding show that the energy absorbed per unit volume of weld, Aq/ (vd), where A is the fraction of incident energy absorbed by the workpiece, governs the cooling time of the weld as well as the width of the HAZ [13].

$$\mathbf{\Delta t = [Aq/ (vd)]^2 (4\Pi\lambda\rho c)^{-1} x [1/ (T_1 - T_0)^2 - 1(T_2 - T_0)^2]} \qquad \textbf{(1)}$$

$$\mathbf{w = Aq/ (vd) [2/ (\Pi e)]^{1/2} (2\rho c)^{-1} x [1/ (T_3 - T_0) - 1/ (T_4 - T_0)]} \qquad \textbf{(2)}$$

T_0 is the initial (or preheat) temperature (K), λ is thermal conductivity (Wm $^{-1}$ K-1), ρ is density (Kg m^{-3}), c is heat capacity (J kg^{-1}K $^{-1}$), and e is the base of natural logarithms (2.718). Assuming optimum welding conditions, taking absorptivity= 0.7; and average material properties corresponding to a temperature of approximately 60% of the melting temperature, equations 1 and 2 quite suitably describe the effect on weld properties by changing process parameters[13].

1.7 BEHAVIOUR OF VARIOUS MATERIALS TO LASER WELDING[13]

- Joints between low-carbon and high-strength low-alloy steels are required in many industrial sectors. These metals are readily laser-weldable, but two main problems are martensite formation in the weld bead or low alloy HAZ, which promotes cold cracking; and the hot cracking observed in fully austenitic metal. High levels of sulphur and phosphorus, in combination with a coarse solidification microstructure and restraint, can lead to solidification cracking.
- Austenitic stainless steels can be laser welded, with the exception of free machining grades which are susceptible to solidification cracking due to high sulphur content.
- Ferritic stainless steels with relatively low carbon and chromium contents are also readily laser weldable.
- Aluminum and copper: They are difficult to melt with lasers due to their high reflectivity and high thermal conductivity [14]. There is also a large difference in melting temperatures, as well as brittle inter-metallic phases are formed. However, by using Nd: YAG laser welding, sound weld beads have been obtained. Good mechanical properties and thermal conductivities are reported.
- Aluminium and Steel: When attempting to weld these metals by normal fusion processes, problems result due to formation of brittle intermetallic compounds and large difference in thermal conductivities. Steel and copper: Differences in their melting temperatures and thermal conductivities, as well as compositional effects, are the main sources of difficulties in joining steel and copper.
- Steel and nickel: The heat resistance of the nickel component is often the determining factor in its selection.
- Aluminium and lead: Successful laser welding of aluminium alloys to lead, for use in instruments, through the use of a tin interlayer has been reported.

1.8 ADVANTAGES AND DISADVANTAGES OF LASER WELDING

1.8.1 Advantages

The heat influence zone is very small due to a very short pulse duration (welding time, 5-10 ms) and a relatively slow sequence of the individual welding pulses (up to 10 Hz). One of the main advantages of laser welding is its versatility. Another important fact is that laser systems can be made fully automatic in order to have high accuracy welds. Improvements in welding speed, productivity and accuracy are achieved at the same time. Very high finish welds are obtained, that do not require further processing. These qualities make lasers a good choice for welding a variety of parts like transmission components, antilock-brake valves; pace-makers, and stainless steel tubes. Lasers provide a high heat concentration that is obtained when the beam is focused to a metal surface, resulting in deep, narrow welds with a minimum of melted metal, which reduce undesirable effects such as distortion and large heat-affected zones (HAZs). The high welding speeds and low scrap rates achieved with the laser process make it cost-effective for stainless steel applications.

1.8.2 Disadvantages

The major disadvantages of laser welding are its associated high costs, difficult operating expertise requiring highly skilled labor and high maintenance costs. Apart from that, there are some other disadvantages also, one of them being the tendency of magnesium to vaporize and create severe voids on the surface, when subjected to laser welding. The slow welding speeds (25 to 250 mm/min.), resulting from the pulse rate and puddle sizes at the fusion point also prove to be major disadvantages. Also, laser welding is efficient only up to depths of 1.5 mm. Any additional energy only tends to create gas voids and undercuts in the work.

CHAPTER

2

LITERATURE REVIEW

During recent years, industries have continuously strived to manufacture products having a number of metal combinations at once. This is done so as to obtain the beneficiary properties of each metal, in the specific parts required, within the same product. The method of joining of metals also serves to save a lot of cost in the final product. For example, in cutting tools, the tooling part is made up of highly wear resistant and hard metals, while the base is made up of steel in order to reduce cost. Metals can be joined to each other by various methods, laser welding being of primary importance in joining dissimilar metals. Joints between dissimilar metals are used in a lot of industries mainly automotive, electronics, power generation, etc.

Among the various metals used in industry, the most basic metal, that serves as the foundation of any industry is steel. Steel is basically an alloy of iron with carbon content between 0.2% and 2.0% by weight. Other alloying metals, such as manganese, chromium, vanadium, etc may also be used to impart certain properties to steel. Two of the most important varieties of steel are mild steel and stainless steel. Mild steel contains 0.16–0.29% carbon by weight and is the most common form of steel due to its cheap cost. Mild steel has a relatively low tensile strength, but it is cheap and malleable. A large number of studies have been conducted in which mild steel or low carbon steel has been laser welded to other materials.

A study by Y.S. Yang and S.H. Lee [1] focuses on the laser spot welding of mild steel plates in automotive applications. Laser beam welding (LBW) and Resistance spot welding (RSW) were performed on mild steel specimen to compare corresponding strengths of the laser welded joints. The welding was performed in two modes, one with a welding time of 1s and rotating speed of 60 rpm, and the other with a welding time of 0.67s and a rotation speed of 90 rpm. The low cycle fatigue strength and residual stress distribution in the weld components were measured and compared with that of RSW values. The results showed that the fatigue strength of laser spot welds was always superior to that of the resistance spot welds.

A recent study by B.S. Yilbas, A.F.M. Arif and B.J. Abdul Aleem [5] in 2008 analyses the thermal stresses developed during laser welding of mild steel sheets. Laser welding of 2 mm thick mild steel sheets was carried out under ambient nitrogen gas, using a 2 kW pulsed CO_2 laser at different frequencies. The residual stress in the weld region was found out using the XRD technique. SEM examination of the microstructures as well as micro-hardness test was carried out. The results showed that the stress field values modeled on the Finite Element Method agreed very well with the XRD results. K.Y. Benyounis, A.G. Olabi, M.S.J. Hashmi [3] studied the weld bead profile and the heat input produced in laser butt welding of medium carbon steel by changing the different laser parameters. A CW 1.5kW CO_2 laser was used to investigate the effects of changing various laser welding parameters on the heat input and weld bead geometry. The penetration width (P), welded zone width (W) and heat affected zone width (WHAZ) was investigated using response surface methodology (RSM). The various laser parameters varied were laser power (1.2–1.43 kW), welding speed (30–70 cm/min) and focal point position (−2.5 to 0 mm). They also developed polynomial equations for predicting the heat input and weld bead geometry. The results showed that the predicted models adequately represented the responses within the welding parameter limits.

Another important literature concerned here is the study of the micro-structural characteristics during the pulsed Nd:YAG laser welding of low carbon steel. Low carbon steel has lower carbon content than mild steel, but in many cases it is similar to mild steel. F. Malek Ghaini, M.J. Hamedi, M.J. Torkamany and J. Sabbaghzadeh [11] examined the effect of changing laser energy, welding speed and duration of welding on the dimensions of the weld, its microstructure and hardness. Laser parameters were varied in ranges of 1-1000 Hz for pulse frequency, 0.2-20 ms for pulse duration and 0-40 J for pulse energy. The low carbon steel employed here was 0.7 mm thick St14 mild steel. The welding length was 5 cm, and after welding the welds were cut and polished for microstructural studies. The microstructures observed were of a variety of materials starting form ferrite at the grain boundary to bainite, martensite and Widmanstatten ferrite in the interior parts. The study concluded that Nd: YAG pulsed laser welding can be used to weld low carbon steels by adopting one of the following methods:

1. High peak power densities and higher travel speeds for lower overlapping
2. Medium peak power densities and medium travel speeds for higher overlapping

Perhaps one of the most important materials in industry, stainless steel continues to play an important role in almost all applications. Starting from corrosion resistant pipes to razor blades, stainless steel is used for various purposes. A lot of literature is available on the laser beam welding of various grades of stainless steels. F.O. Olsen made a study in 1995 in which he compared pulsed CO_2 lasers and Nd: YAG lasers for the processes of laser cutting, welding and hole drilling [8]. For the purposes of pulsed laser welding, AISI 316 stainless steel was welded using an Nd: YAG laser and a superpulsed CO_2 laser, and hot crack sensitivity was checked in both cases. The findings showed less crack sensitiveness with CO_2 laser welds than with the Nd: YAG laser welds.

Laser welding of different grades of stainless steel with other steels also have been reported in large numbers. The influence of the laser beam position with respect to the joint, on weld characteristics [9] was studied by five scientists namely Jose Roberto Berrettaa, Wagner de Rossi, Mauricio David Martins das Neves, Ivan Alves de Almeida and Nilson Dias Vieira Junior. A pulsed Nd: YAG laser was used to analyze the technique of welding AISI 304 stainless steel to AISI 420 stainless steel. Specimens were first welded by positioning the laser beam coincident with the joint, and then by moving the laser beam 0.1 and 0.2 mm towards both the AISI 304 and AISI 420 stainless steel sides. The weld geometry was determined under an optical microscope, and microstructure of the weld bead as well as the heat affected zones (HAZ) was observed under a scanning electron microscope. The mechanical properties of the welded components were determined by Vickers micro-hardness test and tensile tests. The tensile tests showed that fracture occurred outside the weld regions, thus showing that the weld region had a higher tensile strength than the base metals. It was also found out that depending on the amount of shift in laser beam position from the AISI 420 steel towards the AISI 304 steel, the hardness along the cross-section of the weld zone showed gradually reducing values. As is typical in keyhole welding, the variations in laser beam position had no effect on the weld geometry. All the specimens showed uniform joints independent of the welding conditions. The SEM examination showed a very fine grained micro structure, which was basically dendritic in the weld region. S.A.A. Akbari Mousavi and A.R. Sufizadeh [6] published a report in 2009 which contained the experimental studies of Nd: YAG laser welding of AISI 321 and AISI 630 stainless steels. The study was concentrated on the effect of laser power, beam diameter and pulse duration on the depth and width of the welds. They found out that both weld depth and width increased with voltage, while they varied bilaterally with the pulse duration. The microstructures were also studied, and micro-hardness tests were performed to ascertain mechanical properties.

Apart from the various number of studies about laser welding of mild steel and stainless steel, a large number of literature exist which give us a very good idea about the weldability of steel with other materials. These studies are very important as they give a general idea about the parameters to be used while welding steel. Laser welding of tool steel and Kovar (T.A. Mai, A.C. Spowage [14]) revealed a sizeable intermixing of both the individual constituents in the weld region. No hot cracking of the joint was seen, and cross-sections of the weld seam exhibited strong convection currents. The porosity observed in the weld seam had a seemingly visible relationship with the welding speed. With an increase in welding speed, the number of pores decreased while their average size increased and vice versa. Welding of steel with other materials using filler wires has also been investigated. One such investigation is that made by H. Naffakh, M. Shamanian and F. Ashrafizadeh. They studied the welding of AISI 310 austenitic stainless steel with nickel based alloy Inconel 657 [19] using four types of filler materials; Inconel 82, Inconel A, Inconel 617 and AISI 310 stainless steel. The results showed that the weld with Inconel A as filler wire showed the least hot cracking sensitivity and the weld region had the highest strength and elongation properties. Studies have also been done to find out the residual stresses in weld joints and the heat affected zones of hot working tool steels (.40.CrMoV.5.1 and 40.CrMnNiMo. 8.6.4, J.M. Costa, J.T.B. Pires, F. Antunes , J.P. Nobre , L.P. Borrego [10])

The behaviour of dissimilar metal welding between steels and various superalloys has also been widely researched. A superalloy or high-performance alloy having excellent creep resistance at elevated temperatures, and superior mechanical strength. Some examples of superalloys are Hastelloy, Inconel, Waspalloy, etc. These alloys are used as turbine blades in gas turbines and jet engines. However due to their high costs, it is often useful to combine them with cheaper metals like steel, so that only the serviceable part is made up of the superalloy. Autogenous full penetration welding of Ni-based superalloy K418 and alloy steel 42CrMo 3.5 mm thick flat plates were conducted using a 3 kW CW Nd:YAG laser (Xiu-Bo Liu, Gang Yu, Ming Pang, Ji-Wei Fan, Heng-Hai Wang, Cai-Yun Zheng [18]). The parameters varied were laser welding velocity, flow rate of side-blow shielding gas and defocusing distance. SEM evaluations and examination of mechanical properties showed that although the micro-hardness of the weld seam was lower than that of the base metals, the joint was as strong as the base metal. A similar study also dealt with the laser welding of superalloy K418 turbo disk and alloy steel 42CrMo shaft, instead of flat plates (Xiu-Bo Liu, Gang Yu, Jian Guo, Yi-Jie Gu, Ming Pang, Cai-Yun Zheng and Heng-Hai Wang [24]). The results showed that both the tensile strength as well as the microhardness values of the weld region was lesser than that of the base metal.

Among the various metal combinations used in industry, copper-steel and aluminium-steel welded joints are among the most important dissimilar metal joints. Joints between copper and steel are required marine environment as well as in processing of metals [13], as well as in the power generation industry [17]. While welding copper to steel, the high reflectivity of copper to CO_2 laser beam posed some problems. Hence, Chengwu Yao, Binshi Xu, Xiancheng Zhang, Jian Huang, Jun Fu and Yixiong Wu proposed a new method to weld copper-steel successfully [17]. They recommended using a scarf-joint geometry, i.e. instead of the copper and steel welding edges being parallel to each other, they were in acute and obtuse angles respectively. The laser beam was focused on the steel side with the offset dependent on the scarf angle. The experiment resulted in copper-steel joints free of any defects and having excellent tensile properties. T.A. Mai and A.C. Spowage addressed one of the most fundamental defects in copper steel welding, that of hot cracking in the HAZ of steel [14]. In their study, they created copper-steel butt joints by focusing the laser beam 0.2mm into the steel. Although complete metallurgical bonds could not be obtained between steel and copper, the problem of hot-cracking was however solved.

As important as copper-steel combinations, steel to aluminum welded joints are used widely in cryogenic applications [13]. Aluminum is used to construct the storage tanks while steel is used for manufacturing the transfer lines to these tanks. Laser welding addresses a number of problems faced in welding steel-aluminium such as formation of intermetallic compounds [13]. The laser welding of low carbon steel to 6000 series aluminium alloy in a steel-on-aluminium overlap weld was carried out in a three-fold approach: (1) process optimization, (2) material characterization and (3) mechanical testing (G. Sierra, P. Peyre, F. Deschaux-Beaume, D. Stuart and G. Fras [21]). Embrittlement of the weld zone was observed, mainly located on welded aluminium interfaces with thicknesses between 5 μm and 20 μm. The same scientists also performed comparative studies of joining galvanized steel to aluminium by laser and GTAW processes [22]. Laser welding of carbon steel to 5754 aluminum alloy (M.J. Torkamany, S. Tahamtan, J. Sabbaghzadeh [20]) and explosion-welded steel/aluminum structural transition joints (L. Tricarico, R. Spina [23]) have also been reported in different literatures.

In order to obtain a better insight about laser welding of stainless steel to mild steel, study was done of many literatures that presented laser welding between different kinds of steels. Zhang Li, G. Fontana (1998) [2] studied the fully automated laser welding of stainless steel to free-cutting steel used in manufacturing hydraulic valves. The valves were made up of AISI304L non-magnetic stainless steel and AISI12L13 free-cutting steel tubular parts. Solidification cracking and micro-fissuring were controlled by adopting a special laser welding technique. The technique consisted of having a 0.12mm offset of the laser beam towards the AISI304L steel and a 15^{o} angle of impingement. Mechanical testing showed good strength of the welds, high repeatability and good reliability of the various welding parameters adopted.

Z. Sun investigated the feasibility of producing the so called "black/white" joints or ferritic/austenitic (F/A) joints through laser beam welding [4]. The materials used in the investigation process are low alloy Cr-Mo steel 13CrMo44 and austenitic stainless steel AISI 347. A continuous wave (CW) CO_2 laser with maximum power output up to 6.0 kW was used for welding purpose. Sun found out that both autogenous and filler-wire welding methods are suitable for producing weldable joints having good mechanical properties at room temperature. However he also concluded that autogenous welding is not favorable for welding F/A joints due to formation of unwanted martensite in the weld metal microstructure. A 2 kW Trumpf TRUDISK 6002* Yb: YAG laser beam was utilized to join 1 mm thick TRIP780 with 1.5 mm thick DP980 and 1 mm thick mild steel (Rajashekhar S. Sharma, Pal Molian [12]). Results indicated that the laser welds possessed excellent mechanical strength and hardness with minimum number of defects which are attributed to the high beam quality and disk type of laser. Consistent values of hardness were obtained in the fusion zone, although the upper areas possessed higher values of hardness as compared to the lower regions. Tensile testing of all the TRIP steel-MS combinations showed fracturing in the mild steel area. Optimization studies of laser welded F/A components have been done in order to obtain a clearer picture of the relationship between various welding parameters, and to optimize these parameters (E.M. Anawa, A.G. Olabi [7]). A CW 1.5kW CO2 Rofin laser with 127mm focal length high-pressure lenses and 10.6 mm wavelength was used to weld together mild carbon steel and AISI 316 stainless steel plates in a butt joint configuration. A statistical design of experiment (DOE) was formulated in order to optimize selected laser beam welding parameters (power, welding velocity and focus length). Joint strength was determined using the notched-tensile strength (NTS) method. The response values obtained from these studies showed a direct relationship with laser power. In other words higher is the laser power, higher is the response value and vice versa. Higher power results in greater power densities, which lead to deeper penetration and hence higher response values. The tensile strength values were measured in relation to different welding speeds. Irrespective of the focus position, the response values decreased with increasing welding speeds. The highest tensile strength value was observed at a speed of 500mm min^{-1}.

Much of the work already done has been either in laser welding of steel to other materials, or in welding of various grades of stainless steels. Very few works exist that concentrate on laser beam welding of mild steel and stainless steel. In this present study, we concentrate on finding the effect of change in laser welding parameters (pulse energy and welding speed), on the various tensile strength of the joint formed. This will help us find better methods to use both the cheap nature of mild steel and the strength of stainless steel at once, in form of welded joints.

CHAPTER

3

MATERIALS

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METHODS

3.1 MATERIALS

The raw materials selected for this study were mild steel and stainless steel. A mild steel sheet of approximately 1.53mm thickness and a stainless steel sheet of approximately 1.52 mm thickness were selected for this purpose. It was seen that there was no rusting in the steel sheets.

3.2 SPECIMEN PREPARATION

The metal sheets were cut into small plates of length 0.8mm and breadth 0.3mm with an orbital jigsaw machine. The edges of all the plates were ground with a pedestal grinder to attain a smooth surface finish. It was also taken care to ensure that the edges remained almost parallel to each other so that when two plates were placed side by side, there was no gap between them.

Fig 3.1: Pedestal grinder

3.3 LASER WELDING

3.3.1 Apparatus and equipment

A pulsed Nd: YAG laser system (ALPHALASER AL200) with a maximum average output power of 200 W is to be used. Pulse width can be varied between 0.5 an 20 ms at a maximum pulse frequency of 30 Hz. The maximum pulse energy is 80 J, peak power 9 KW with laser spot size varying from 0.3 – 2.2 mm. The laser beam is delivered to the workpiece by mirrors and focused by 150 mm lens. The following table gives the detailed technical specifications of the laser welding equipment used.

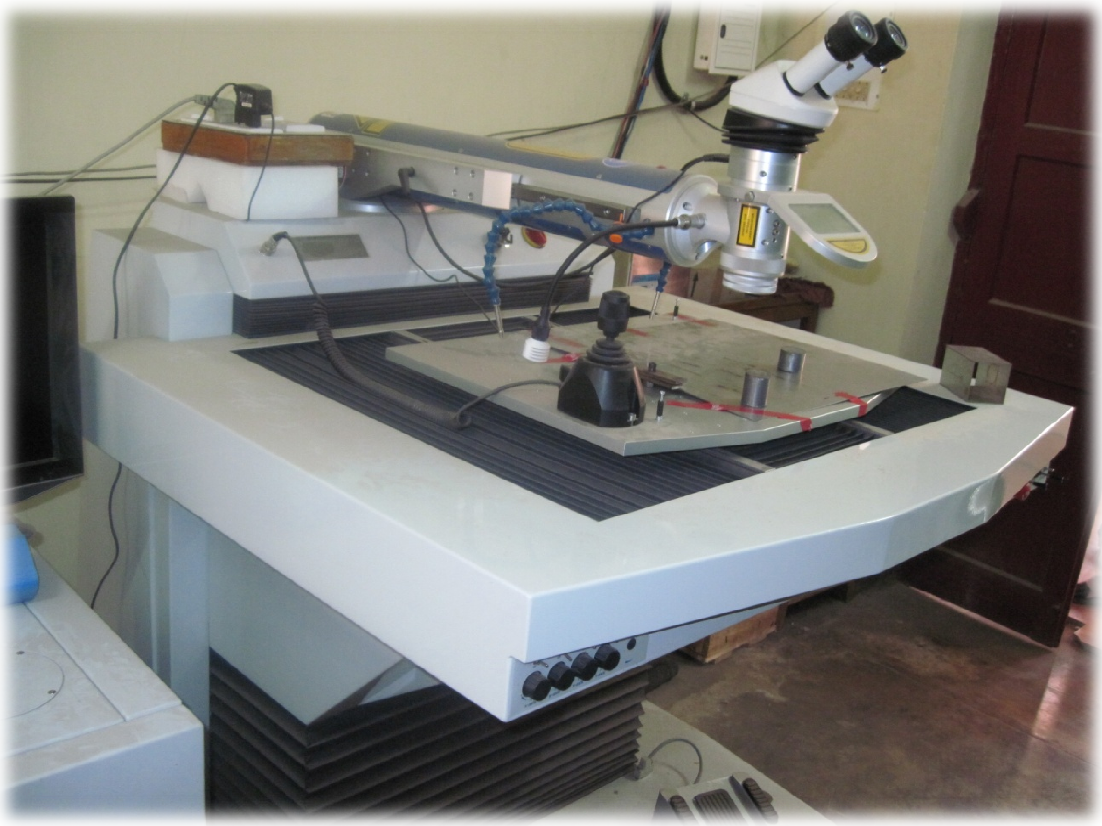

Fig 3.2: ALPHALASER AL200 Nd: YAG laser apparatus

TABLE 2: Specifications of the laser equipment

TECHNICAL DATA	**AL 200 SPECIFICATIONS**
LASER	
Wavelength	1064 nm
Average power	200 W
Peak pulse power	9 KW
Pulse energy	150 mJ – 80 J
Pulse duration	0.5 ms – 20 ms
Pulse frequency	Single pulse, 20Hz – 30 Hz
Welding spot diameter	0.3 mm – 2.2 mm
Pulse shaping	Adjustable power-shaping within a laser pulse
Control	User-specific operation with up to 128 parameter sets
Focusing lens	150 mm
VIEWING OPTICS	Leica binocular with eyepieces for spectacle users
POWER SUPPLY	
Dimensions (L*W*H)	820*400*810 mm
Weight	Approx 98 Kg
LASER BEAM SOURCE	
With focusing unit (length *diameter)	1100*120 mm
Weight	Approx 20 Kg
ELECTRICAL SUPPLY	3*400V / 3*16 A / 50-60 Hz / N, PE
COOLING	Air cooled with internal cooling water-circuit, no additional external cooling is necessary.

3.3.2 Software

The software used in the CNC equipment was WIN Laser NC software (NC 4-axis control)

3.3.3 Choice of parameters

For the welding purpose, the focused beam diameter was fixed at 1.8 mm. After fixing the beam diameter, two sets of specimen were taken as follows:

1. Welding speed constant (2 mm s^{-1}) and variable beam energy:

9.6J, 10.5J, 10J, 15J, 11J, 11.5J, 12J and 13J

2. Beam energy constant (10 J) and variable welding speed:

2 mm s^{-1}, 3 mm s^{-1}, 3.6 mm s^{-1}, 4.2 mm s^{-1}, 5 mm s^{-1}, 1.6 mm s^{-1} and 6 mm s^{-1}

3.3.4 Welding process

The mild steel and stainless steel plates to be welded were carefully placed such that there was no gap between the edges to be welded. The alignment was ensured with the help of the microscope provided in the laser apparatus. The plates were then welded for a length of 0.25 mm. This procedure was repeated for all the selected sets of parameters.

The following figures show the welded seams of all the specimens as used in the laser welding experiment:

Case 1 (constant welding speed and varying beam energy)

Fig 3.3: energy = 9.6J

Fig 3.4: energy = 10.5J

Fig 3.5: energy = 10J

Fig 3.6: energy = 15J

Fig 3.7: energy = 11J

Fig 3.8: energy = 11.5J

Fig 3.9: energy = 12J

Fig 3.10: energy = 13J

Case 2 (constant beam energy and varying welding speed)

Fig 3.11: speed = 2 mm s^{-1}

Fig 3.12: speed = 3 mm s^{-1}

Fig 3.13: speed = 3.6 mm s^{-1}

Fig 3.14: speed = 4.2 mm s^{-1}

Fig 3.15: speed = 5 mm s^{-1}

Fig 3.16: speed = 1.6 mm s^{-1}

Fig 3.17: speed = 6 mm s^{-1}

3.4 TENSILE TESTING

After welding was completed, all the specimens were subjected to tensile testing in a universal testing machine (UTM). The load v/s displacement values of each specimen were noted. Also the peak loads in case were also found out and recorded.

Fig 3.18: Universal Testing Machine (UTM)

CHAPTER

4

RESULTS

&

DISCUSSIONS

4.1 EFFECT OF CHANGING BEAM ENERGY AT FIXED WELDING SPEED

With the help of the data obtained from the tensile testing, load v/s displacement curves were drawn for each specimen. Displacement (mm) was taken along X-axis and load (kN) was taken along Y-axis. The following figures show the test results of each specimen as obtained from the automatic recording unit of the UTM.

Case 1 (constant welding speed and varying beam energy).

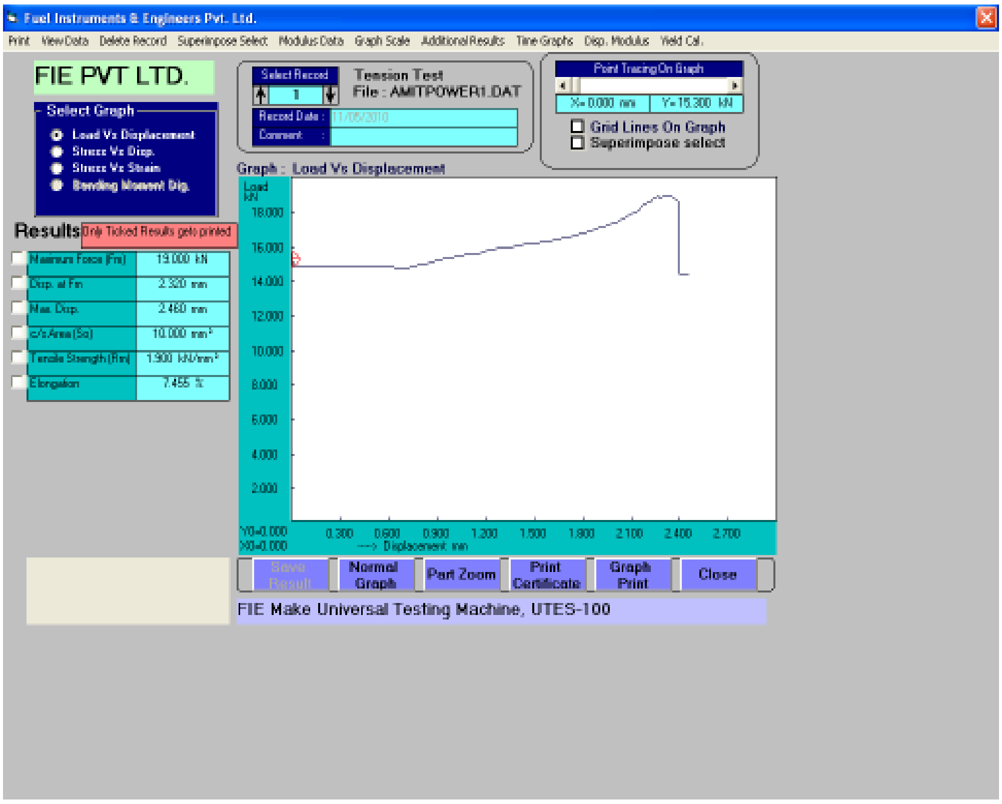

Fig 4.1: energy = 9.6J

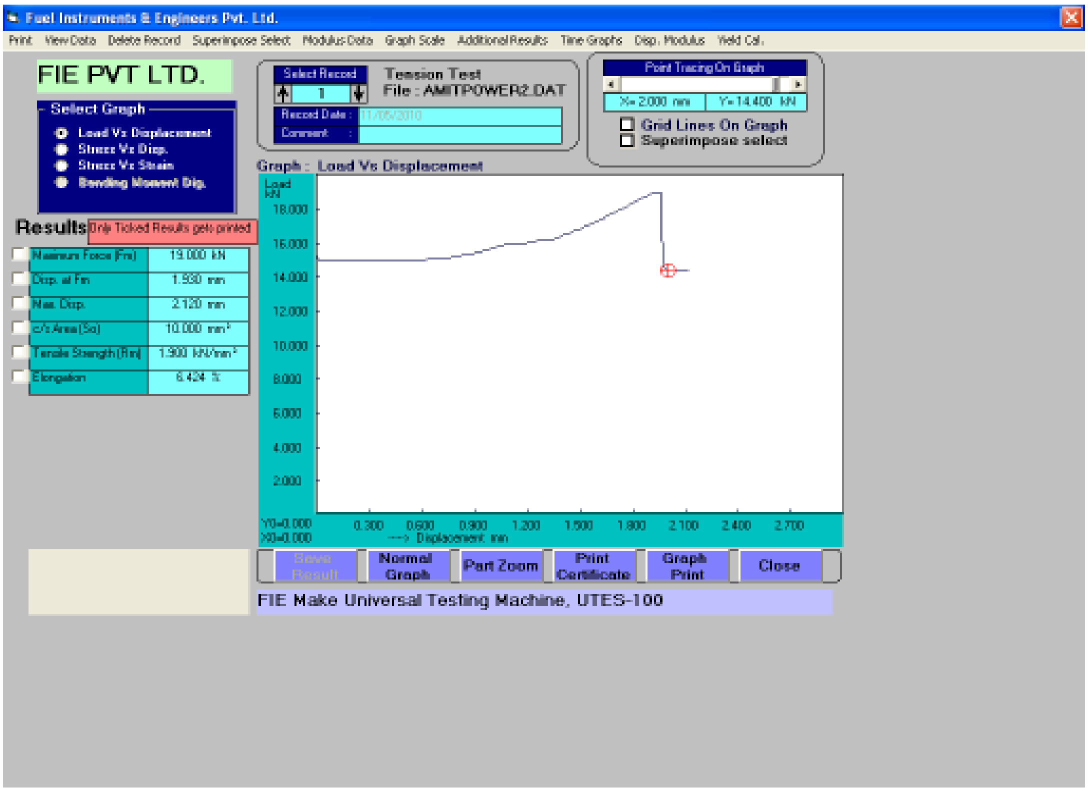

Fig 4.2: energy = 10.5J

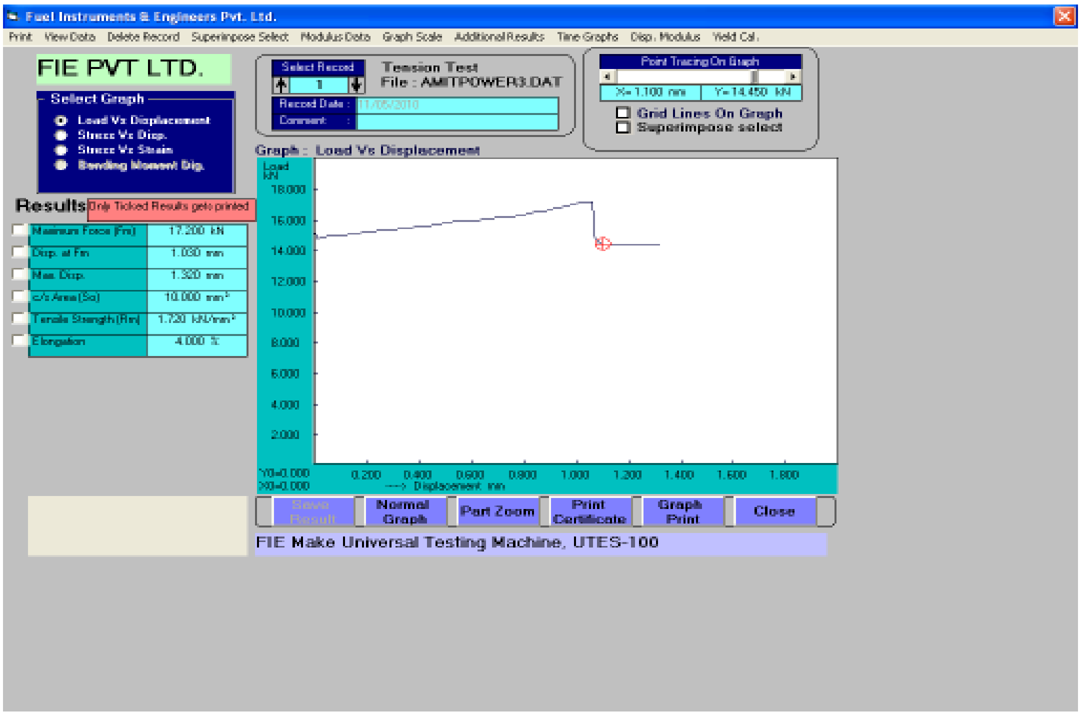

Fig 4.3: energy = 10J

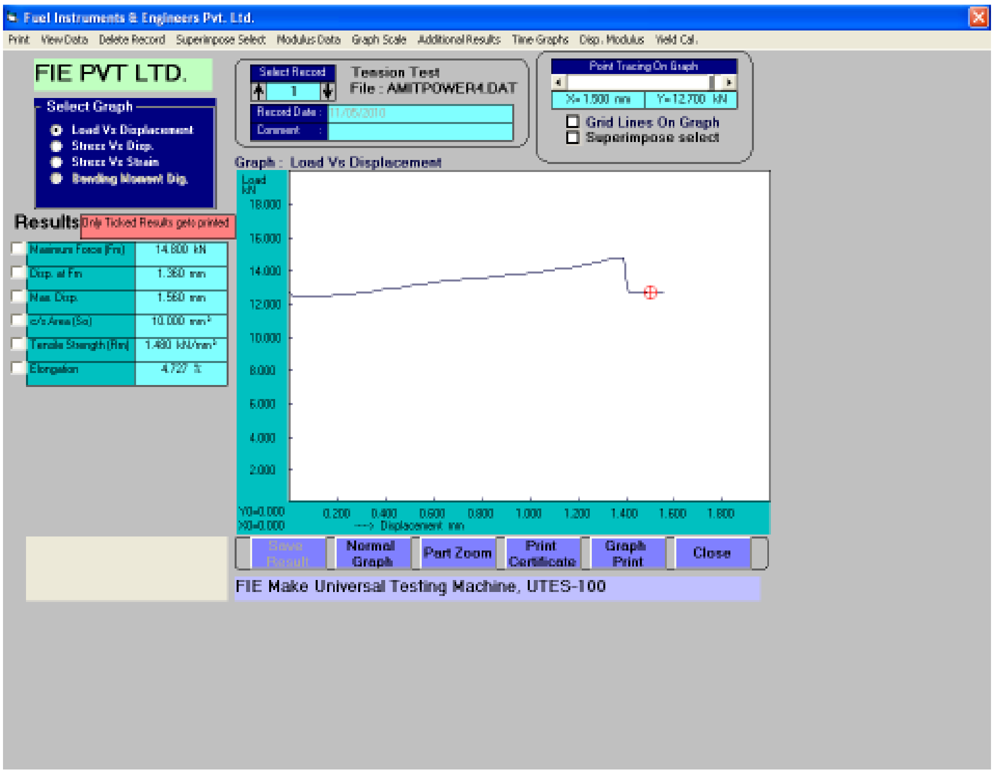

Fig 4.4: energy = 15J

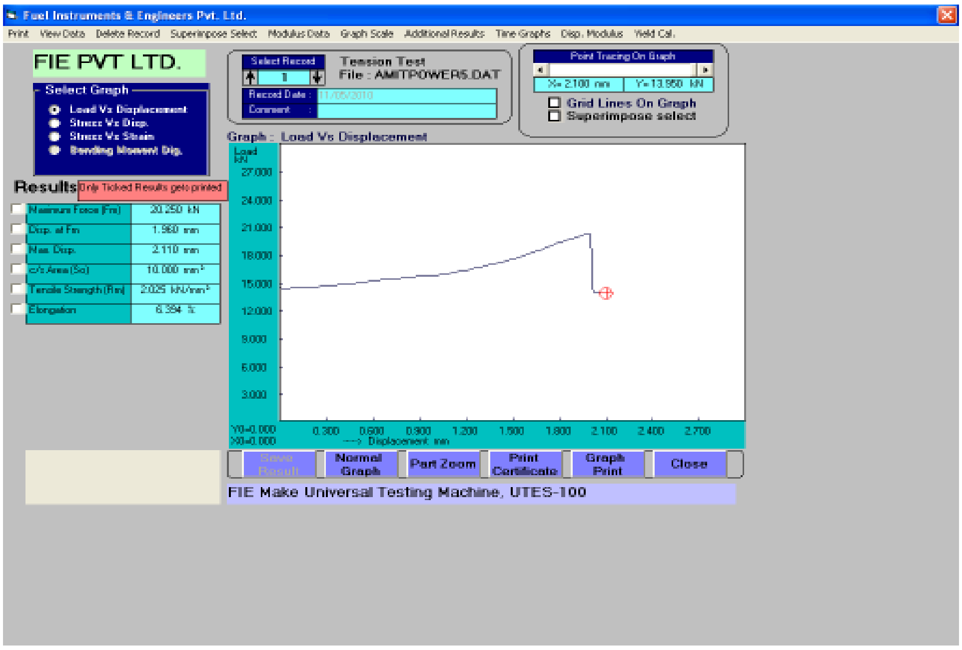

Fig 4.5: energy = 11J

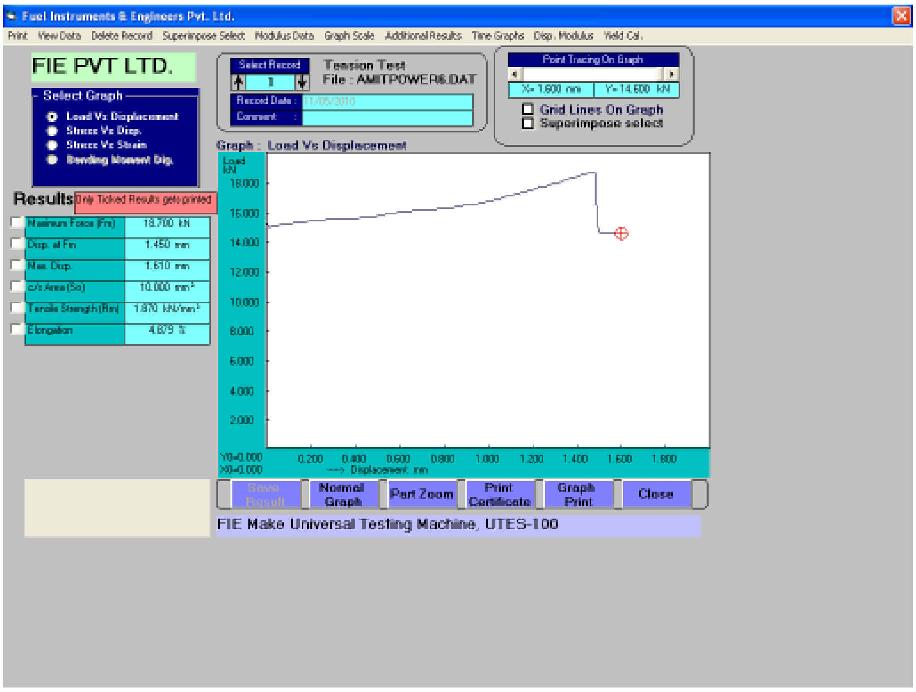

Fig 4.6: energy = 11.5J

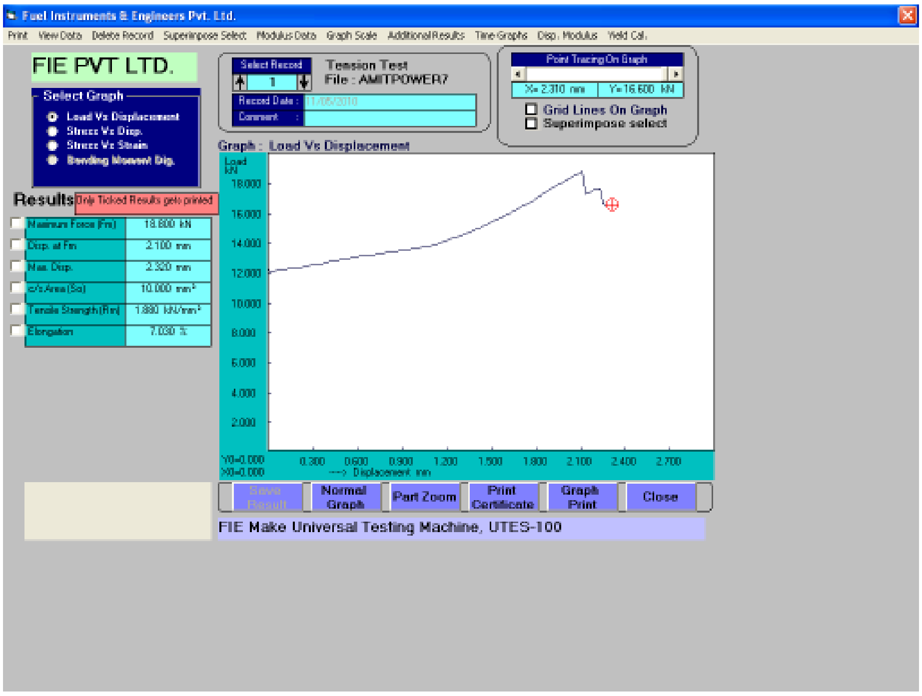

Fig 4.7: energy = 12J

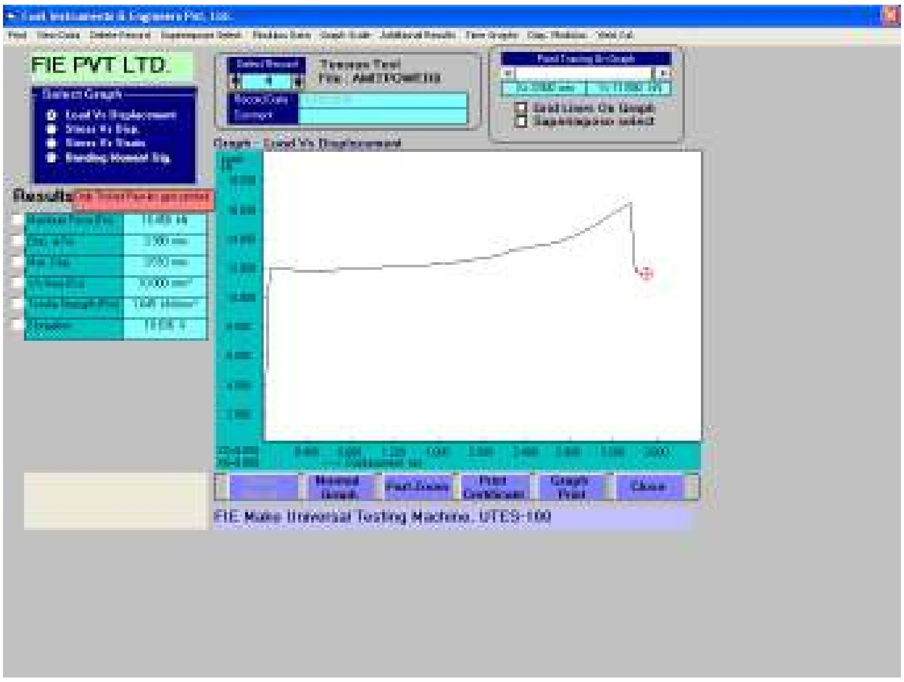

Fig 4.8: energy = 13J

The following graph shows all the eight curves on the same graph for comparison purposes.

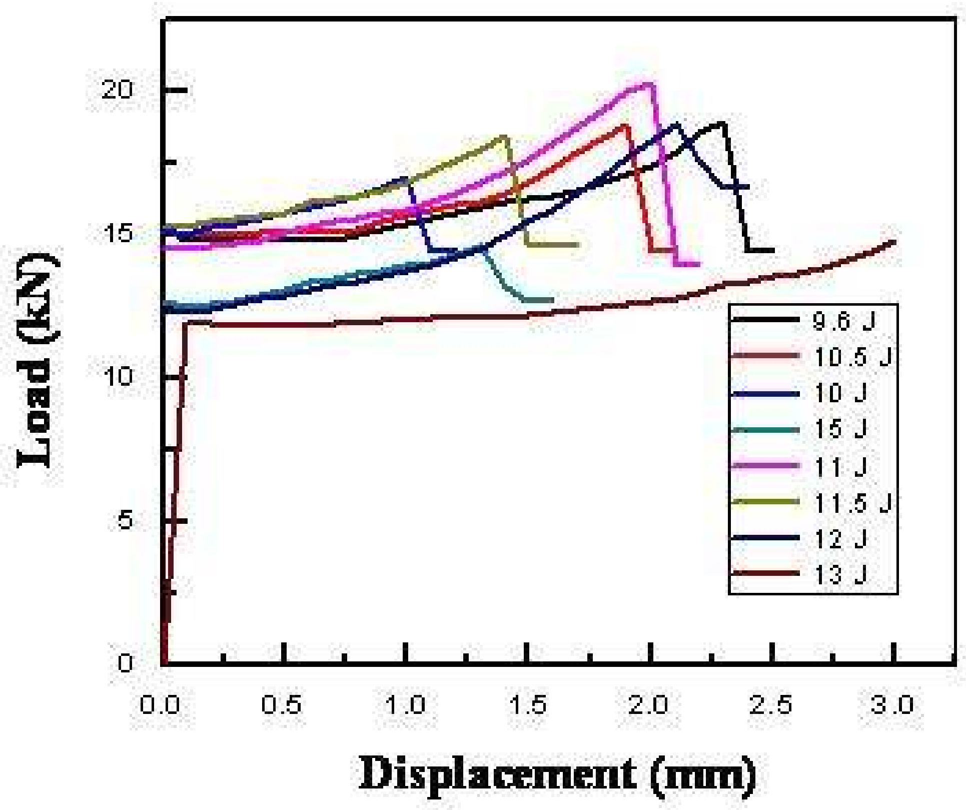

Fig 4.9: Load v/s Displacement curves of all specimens for varying beam energy

From the graphs above we clearly see that as displacement, also known as the elongation increases, the load on the welded joint also increases. The load continues to increase till a point is reached at which the joint can no longer elongate and it breaks. The load at this point is called the peak load and is a representative quantity of the strength of the joint. Higher is the peak load, the stronger is the joint. The following figure shows the graph between beam energy and the corresponding peak loads of all the specimens. Energy (J) is taken along X-axis while peak load (kN) is taken along Y-axis.

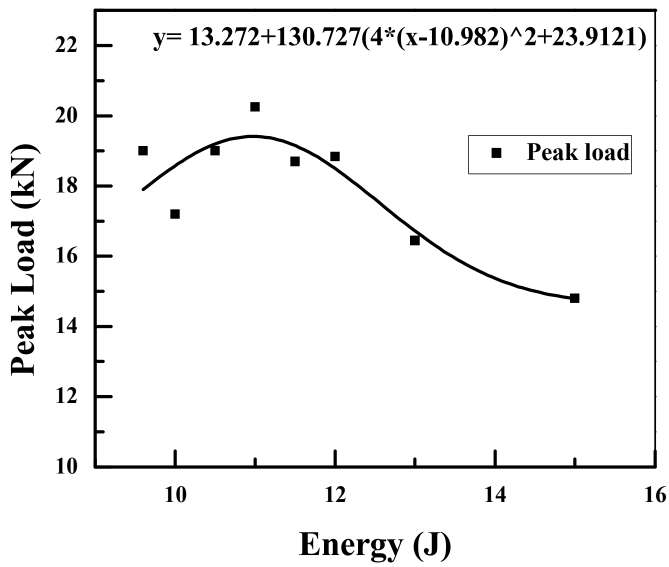

Fig 4.10: Peak load v/s Energy curve at a constant welding speed

From the figure, we see that the peak load increases with increasing beam energy, attains a peak value at an optimum energy and then again decreases with increasing values of energy. At this optimum energy, the power is just sufficient to cause full penetration of the weld bead, resulting in formation of a uniform weld region having good strength. Any levels of energy less than this value won't have enough power to cause full penetration of the weld bead, thus resulting in a weaker joint. While at beam energies higher than the optimum value, excessive power causes burn through of the weld region. The joint gets weakened in the middle thus resulting in lower peak loads. In this experimental process, beam energy of 11 J was found out to be the optimum value. A polynomial equation was derived to find the relationship between peak load and beam energy. The equation found out was as follows:

$$PL = 13.272 + 130.727(4(E - 10.982)^2 + 23.9121)$$

Where: PL = Peak Load (in kN)

E = Beam Energy (in Joules)

4.2 EFFECT OF CHANGING WELDING SPEED AT FIXED BEAM ENERGY

Taking displacement (mm) along X-axis and load (kN) along Y-axis, load v/s displacement curve of each specimen was plotted using the automatic recording unit of the UTM. The following figures show the plots obtained for each specimen.

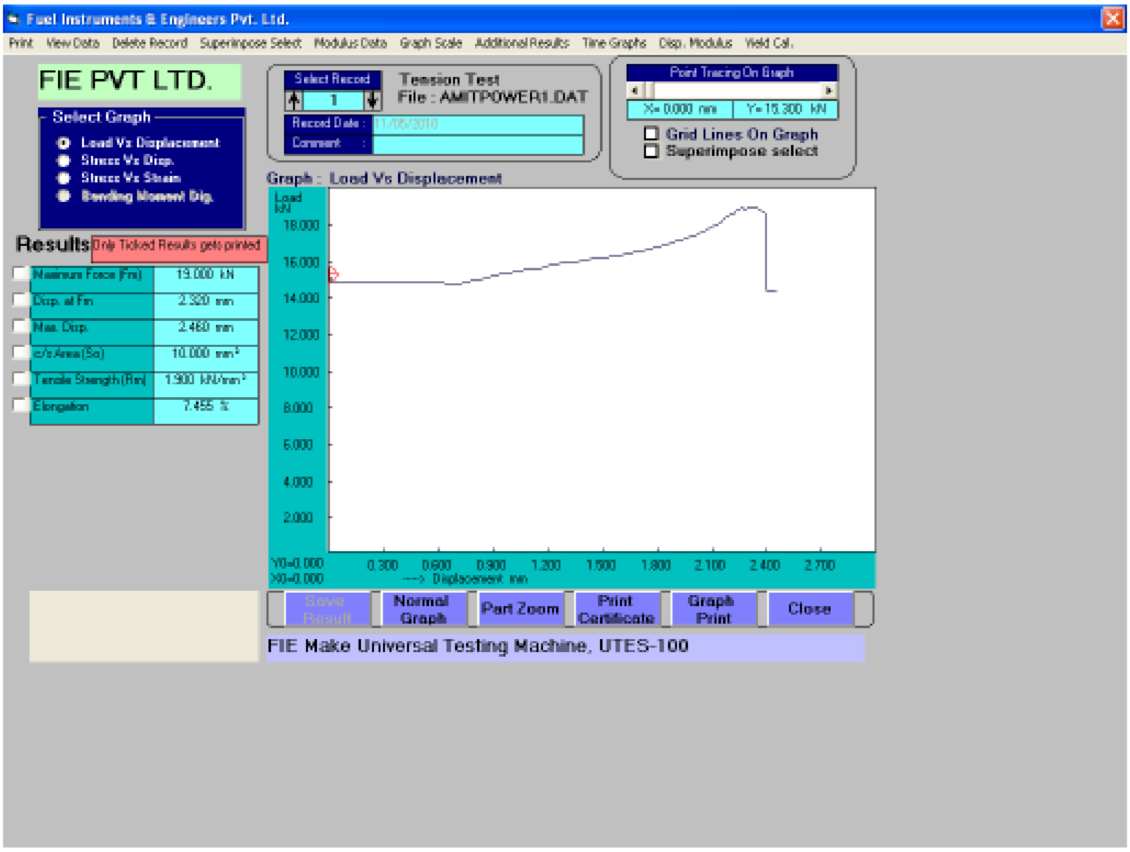

Fig 4.11: speed = 2 mm s^{-1}

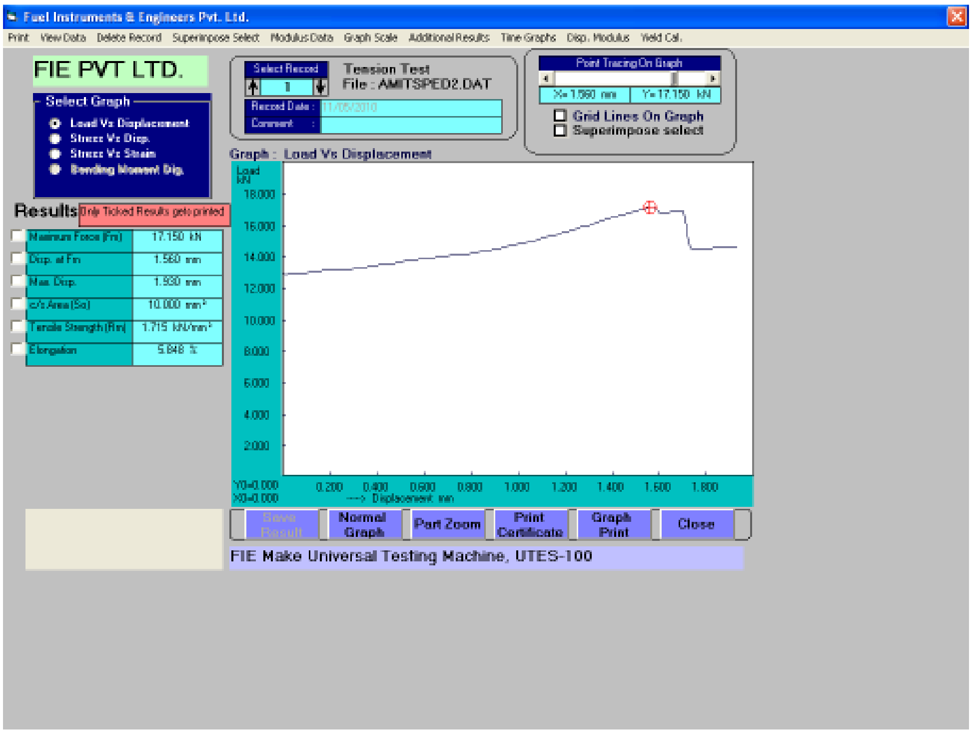

Fig 4.12: speed = 3 mm s^{-1}

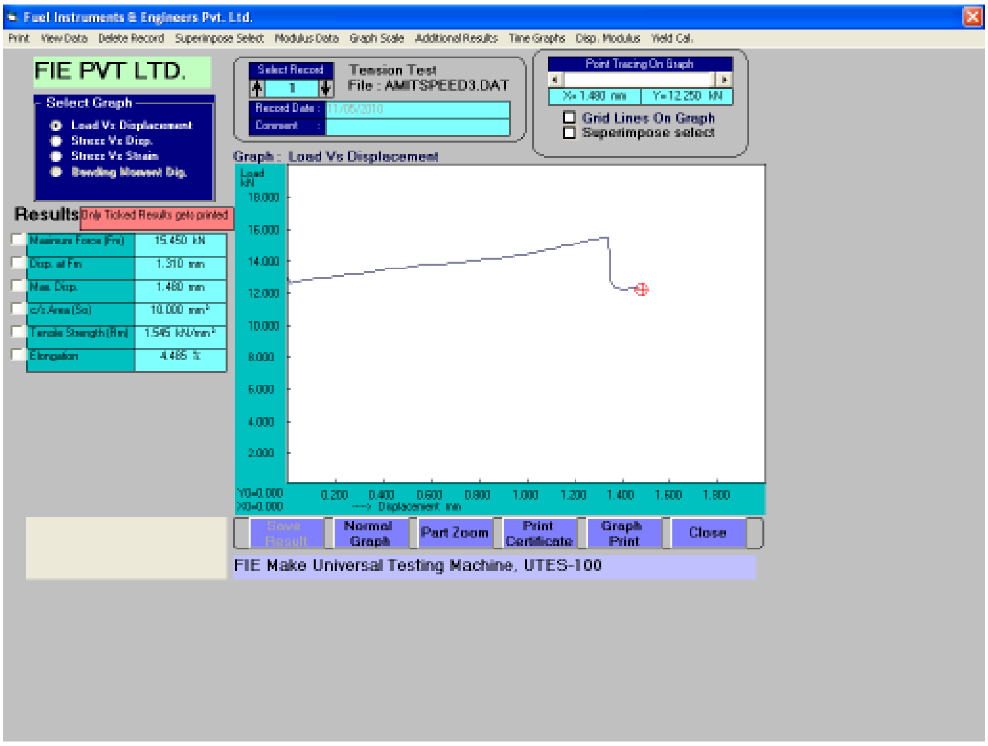

Fig 4.13: speed = 3.6 mm s^{-1}

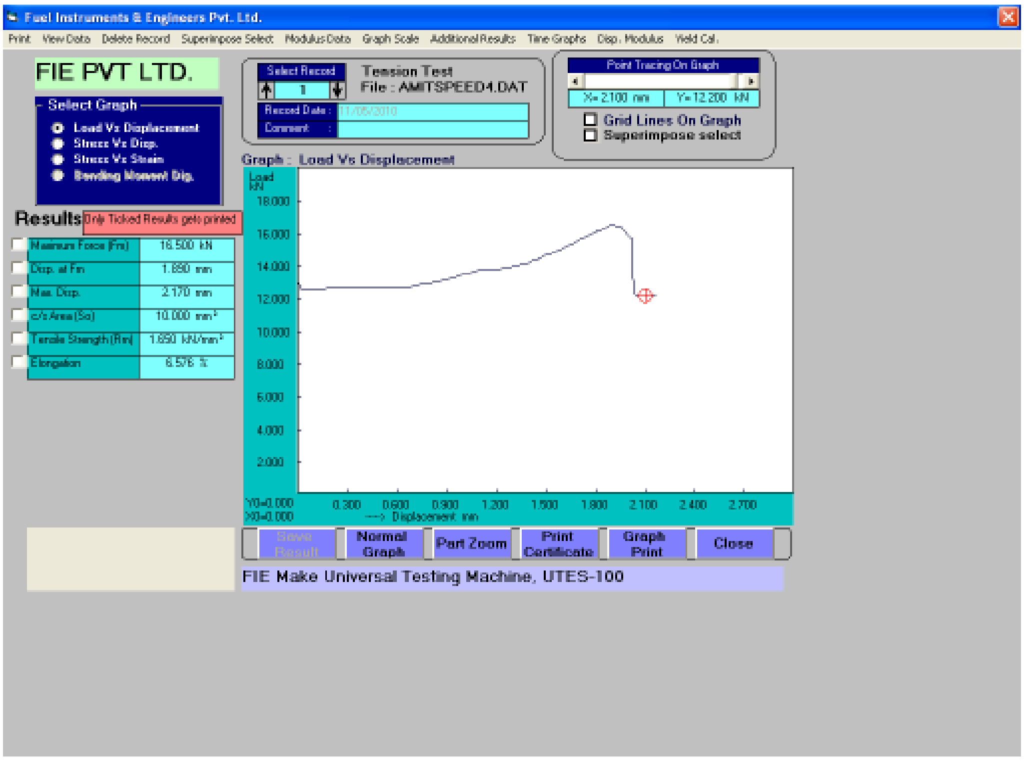

Fig 4.14: speed = 4.2 mm s^{-1}

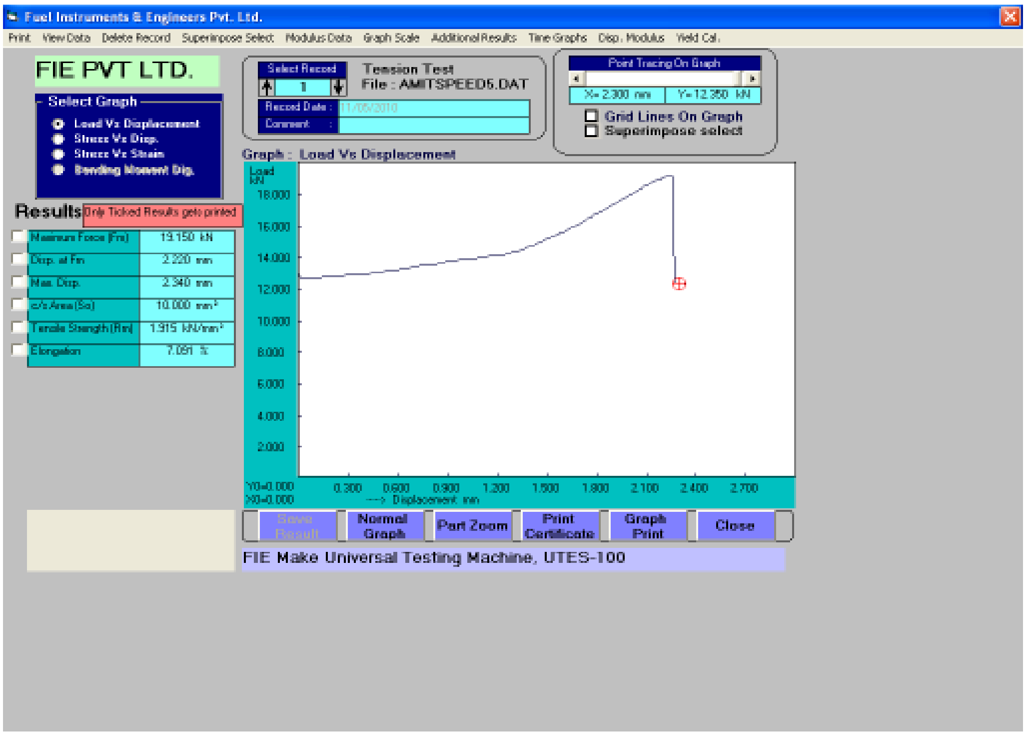

Fig 4.15: speed = 5 mm s^{-1}

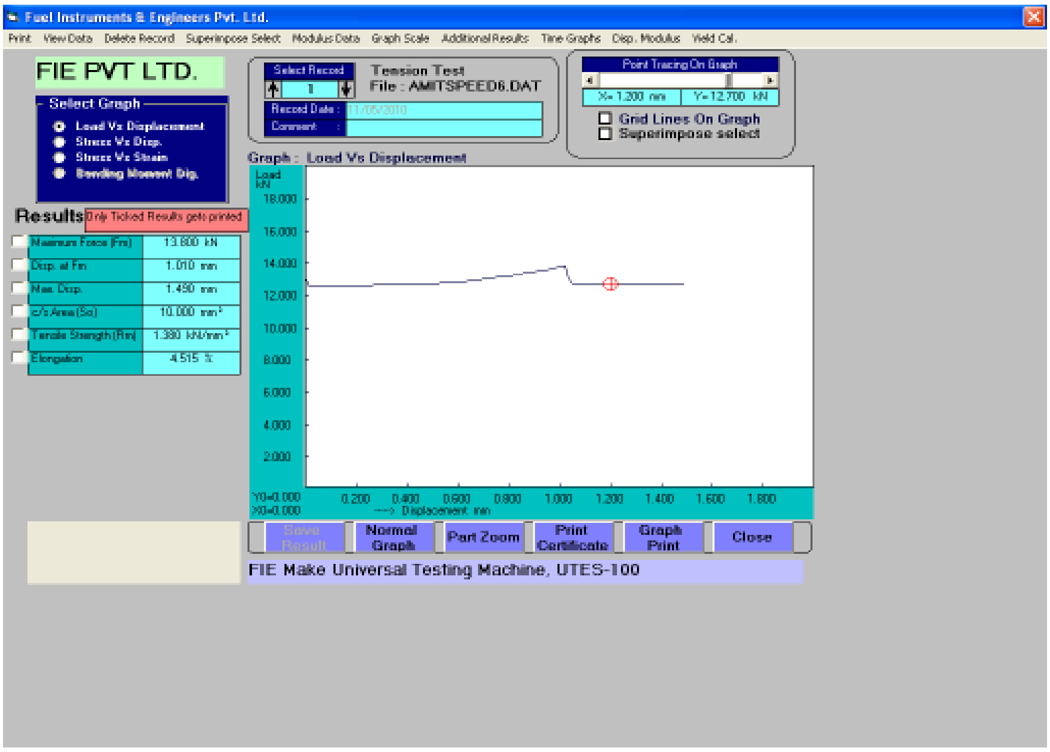

Fig 4.16: speed = 1.6 mm s^{-1}

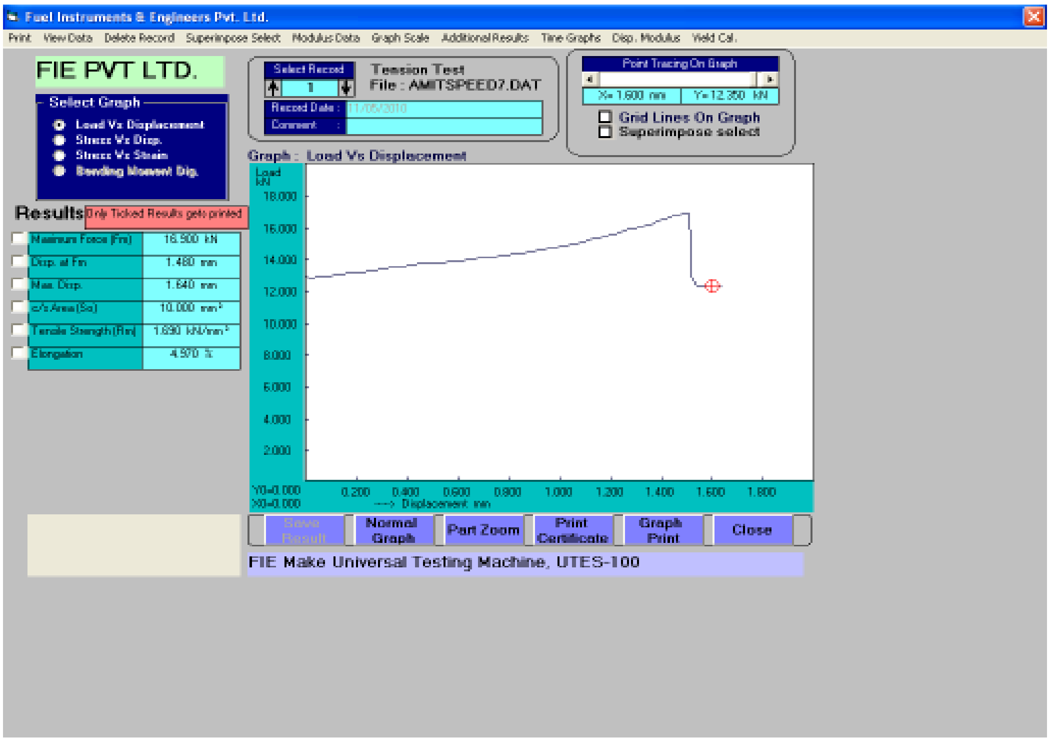

Fig 4.17: speed = 6 mm s^{-1}

After obtaining the plotted graphs for each specimen, all the graphs were plotted on a single graph for comparison purposes.

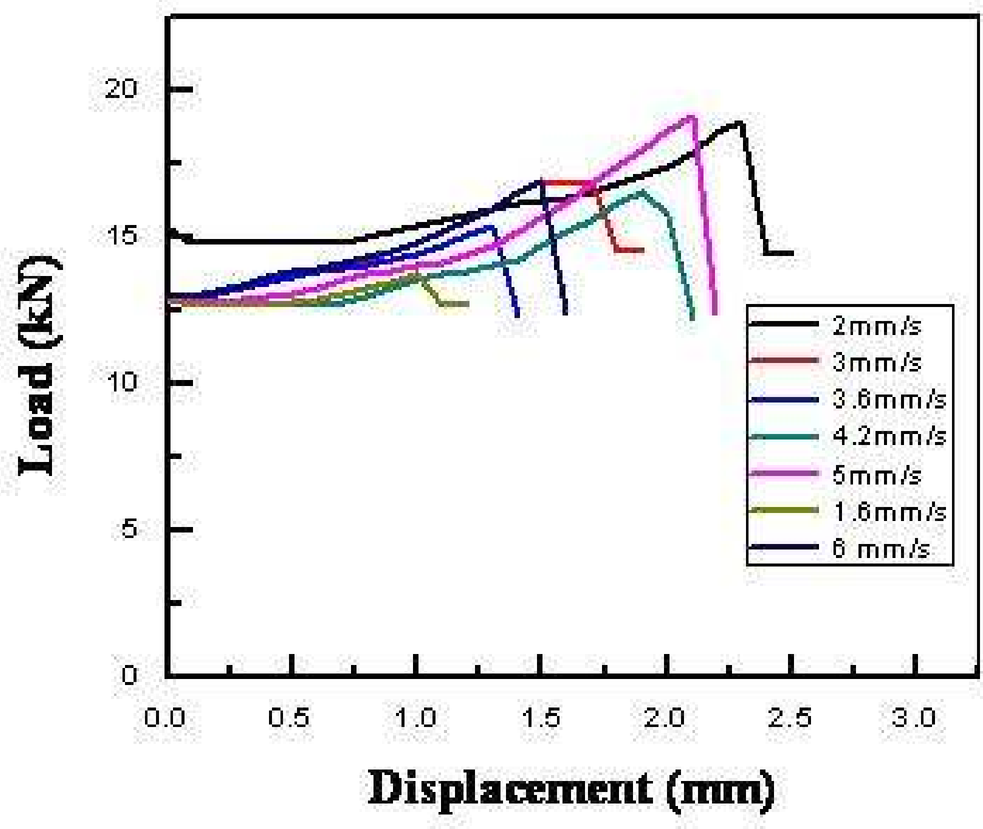

Fig 4.18: Load v/s Displacement curves of all specimens for varying welding speed

These graphs also reveal the same trend as we found out in case of variable beam energy. The load carried by the joint increases with increasing elongation, attains a peak value and then the weld joint fails by rupture showing sudden decrease in the load carrying capacity. The peak loads in case were recorded and a graph was drawn taking welding speed (mm s^{-1}) along X-axis and peak loads (kN) carried along Y-axis.

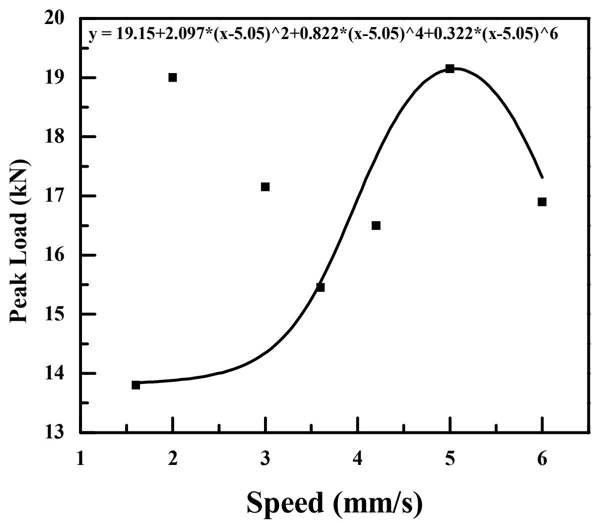

Fig 4.19: Peak load v/s Speed curve at constant beam energy

As is seen from the graph, peak load values continue to increase with an increase in welding speed, the slope also gradually increasing. After attaining a maximum value, the peak load strength of the joint decreases with decrease in welding speed. Higher welding speeds will lead to incomplete welding between the metal plates. In other words, before the metals have welded and bonded together fully, the laser beam moves to a new position. Thus the joint formation is incomplete and hence its strength is less. At very low welding speeds, the same problem arises as did arise during higher beam energies. The weld region gets burned through due to the laser beam staying at the same point for a longer duration than is required. Thus there lies an optimum welding speed at which the tensile strength of the joint is a maximum. From the data obtained in the experiment, a welding speed of 5 mm s^{-1} produced the best results. The relationship between Peak Load and welding speed was found out to be:

$$PL = 19.15 + 2.097(S - 5.05)^2 + 0.822(S - 5.05)^4 + 0.322(S - 5.05)^6$$

Where: PL = Peak Load (in kN)

S = Welding Speed (in mm s^{-1})

CHAPTER

5

CONCLUSIONS

1. Nd: YAG laser welding of mild steel and stainless steel was carried out by keeping the focal diameter constant (1.8 mm) and varying the other two main laser welding parameters, i.e. first welding speed was fixed and laser beam energy was varied; and then beam energy was fixed and different welding speeds were used.

2. Keeping welding speed constant, the peak load first increased with increasing beam energy, attained a maximum value at a value of 11J, and then decreased with increasing laser beam energy. The relationship between beam energy and peak load was found to be

$$\text{Peak Load} = 13.272 + 130.727(4(\text{Energy} - 10.982)^2 + 23.9121)$$

3. For a fixed value of laser beam energy, with an increase in welding speed, the peak load carrying capacity of the joints first increased, attained a maximum value at a welding speed of 5 mm s^{-1}, and then decreased with increasing welding speed. The equation depicting the relationship between peak load and welding speed is as follows:

$$\text{Peak Load} = 19.15 + 2.097(\text{Speed} - 5.05)^2 + 0.822(\text{Speed} - 5.05)^4 + 0.322(\text{Speed} - 5.05)^6$$

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